ON SOIL MOISTURE MAPPING USING IR-THERMOGRAPHY

Sune R.J. Axelsson

Department of Electrical Engineering
Linköping University
S-581 83 Linköping, Sweden

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ABSTRACT

This paper presents some experimental and theoretical results on the relationships between the thermal IR-signature and soil moisture. Comparative groundbased experiments were performed in order to investigate how the albedo, emissivity and surface temperature of thin soil layers depend on soil water content for three different soil types (sand, clay and humus). Results from both experiments and computer simulations show that the evaporative heat flux has a very significant effect upon the surface temperature of wet soils in the daytime. By night and when the soil dries up, in particular, the thermal inertia and its coupling to water content becomes much important. Furthermore, it is obvious from the experimental results that the soil moisture effects on emissivity, albedo and evaporation show quite different behaviour, which also varies with the type of soil.

1. INTRODUCTION

IR-thermography from airborne platforms has been identified as a promising technique for mapping the evaporation and water contents of bare soils [1] - [3]. The use of sensors on board satellites, such as LANDSAT-TM with a pixel size of 120 m or NOAA-AVHRR (1100 m) means repetitive coverage and an enormous increase of mapping capacity. A main problem at the data analysis, however, is the strong interference from other parameters than soil moisture, which reduces the accuracy of the interpretation procedure.

The aims of this study were to further improve the present knowledge of the thermal IR signature of soils and its dependence on water contents and soil type. At the experiment, the emissivity and surface temperature of thin wetted soil-layers were measured during the drying phase. As a comparison, measurements of the short-wave reflectance at 0.5 to 0.6 micrometers were also included. From the results, it was possible to estimate how the emissivity, short-wave reflectance and the temperature contrast of different soil types are influenced by the water content and the evaporation losses.

2. PHYSICAL BACKGROUND

The thermal radiation from a surface depends primarily on three factors: surface temperature, emissivity, and reflected radiation from the sky and the environment. The surface temperature itself is determined by the net radiation, the heat exchange with the atmosphere (due to the sensible and latent heat fluxes), the thermal conductivity (λ) and the heat capacity (C) of the ground material.

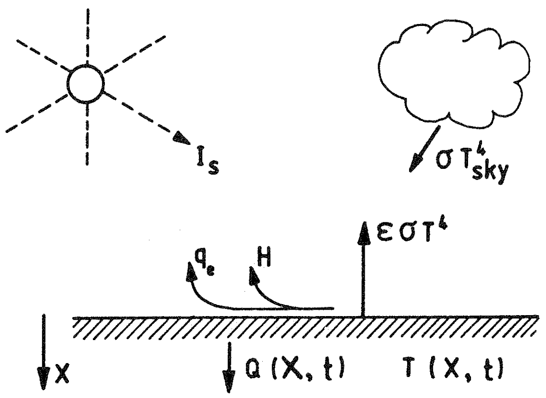
Of particular importance is the thermal inertia of the top layer ($P=\sqrt{\lambda C}$), which influences the day-to-night variations of the surface temperature. The reflectance of solar radiation (albedo) and surface humidity have significant effects on the net radiation and the latent heat flux and by that on the surface temperature as well.

Figure 1 summarizes the analytical relationships involved. The downward heat flux and the temperature field in the soil are determined by two partial equations with the heat exchange at the surface as boundary condition:

$$Q = NE - H - LE$$

where Q is the downward heat flux at the surface, NE is the net radiation, H is the sensible heat flux and LE is the latent heat flux due to evaporation.

THERMAL MODEL OF BARE GROUND



Basic relationships:

$$Q = -\lambda \frac{\delta T}{\delta x}$$

$$\frac{\delta Q}{\delta x} = -C \frac{\delta T}{\delta t}$$

Boundary condition:

$$Q(0,t) = (1-A)\, I + \varepsilon \sigma \left(T_{sky}^4 - T^4\right) - H - q_e$$

Figure 1. One-dimensional model for predictions of the heat flux and temperature field of the top soil.

3. METHODOLOGY

During August 1983 and June/July 1986 ground based IR-measurement were carried out using an IR-radiometer of type Barnes PRT-5, which has a field of view of two degrees and detects the thermal radiation in the wavelength interval 9.5 to 11.5 micrometer.

Besides emissivity and temperature measurements, the reflectivity of the soil samples were measured in 0.5 to 0.6 micrometer using a Hagner S2 photometer. Soil types used at the experiment were quartz sand, clay and humus. Thin layers (5 to 10 mm) of these soils were placed on dishes of 0.3 m diameter. Before the start of the measurement, the samples were wetted. The reflectance, emissivity, temperature and weight changes were then measured during the following drying phase.

At the emissivity measurements, the soil samples were placed on the bottom of a shallow box (0.9x0.7x0.2 m). The top of the box was covered by two flaps, which could be turned aside, exposing the soil samples to the cold sky. The IR-radiometer was put on a tripod above the box with its beam of sensitivity pointing down at the soil sample through a hole (0.14x0.20 m) in the flaps.

By comparing the changes of the measured IR-temperature, when the flaps were turned aside for (i) a reference surface with known emissivity and (ii) the soil sample, it was possible to estimate the soil emissivity. This method of emissivity estimation was further analyzed in [4] .

On June 1986 another experiment was carried out with the same type of soil types as for the earlier emissivity and reflectance measurements. A main objective of this experiment was to compare the changes of the short-wave reflectance and IR-temperature of thin soil layers, when the soil moisture varied. This is an important issue since visible/near-IR and thermal-IR sensors are both considered as main candidates for soil moisture sensing. The information gained from such experiments is also of significant interest for the detailed modelling of the albedo and evaporative influence on the IR-temperature of a semi-dry soil surface.

4. EXPERIMENTAL RESULTS

Figures 2 and 3 display reflectance and emissivity versus soil moisture measured at the experiment August 1983. The graphs of Fig.2 show that the emissivity of sand is changed from 0.90 for dry sand to 0.94-0.96 for high water contents. The emissivities of the clay and humus soils decrease only one or two per cent when the soil samples dry up. It is also observed that the emissivity of sand is close to the dry value of emissivity for soil moisture contents lower than ten per cent, while the fine-grained soils (clay and humus) approach the dry emissivity limit at about 20 per cent.

The results of the reflectance measurements show a quite different soil-moisture dependence than in the thermal-IR band. All soil-types look wet and dark (i.e. low reflectivity) as long as the soil moisture by weight exceeded 10 - 15 per cent. They also show very significant differences in reflectance between the dry and wet states. Typically, the reflectance of dry soils is about twice the wet value. The absolute reflectance values depend also upon the soil type, however. Hence, wet sand or light clay may be misinterpreted as a dry humus soil on imagery in the visible or near-infrared wavelength bands.

Figure 4 shows the time variations of the measured IR-temperature and the reflectance of the three soil types, and in Figure 5 the thermal IR-contrasts between the semi-wet soil samples and the reference samples, which were kept dry during the whole experiment, are displayed.

Figs. 4 and 5 indicate that the reflectance starts moving towards the reflectance value of dry soil before the IR-temperature makes a similar change. The reflectances of the drying soil samples also reach the dry value significantly earlier than the IR-temperatures, which have a more prolonged transition phase. In Figure 4 as in Figure 2, the reflectance of sand is changed more gradually during the drying phase than for the fine-grained soils.

This important difference between visible/near-infrared imagery and the thermal-IR ones is due to the fact that some evaporation is going on even after the upper skin layer of the soil has become dry, while the reflectance is more strictly related to the surface conditions.

Comparisons of the reflectance/soil-moisture dependence for the two different experiments in 1983 and 1986 showed similar relationships for sand. For the humus soil and clay, however, the increase of the reflectance started in 1983 at somewhat lower water contents than in 1986, which probably is due to differences in solar exposure. In 1986, the evaporative demand was larger, which reduced the surface soil-moisture compared with that of deeper layers. The increased diffusion resistance to water flow in fine grain soils like clay prevents a compensation. Hence, the measured average soil water content of the top centimetre overestimates the soil moisture at the surface.

Figure 6 shows the strong near-linear relationship between the IR-temperature contrast and the water losses by evaporation (g/hour). Obviously, the thermal IR contrast is useful for estimations of the latent heat flux and evaporation rate. Further improvements might be possible by also taking into account the effects of albedo and net radiation on the IR-contrast. Figure 7 displays how the measured evaporation (g/hr) is related to the gravimetric soil moisture during the drying phase.

Figure 8 shows the measured relationship between the IR-signal and the gravimetric soil moisture for a clay field, which was irrigated two days before the measurement. From Figs. 7 and 8, the daytime IR-temperature of a clay surface seems to be most sensitive to soil moisture variations in the range of 5 to 15 per cent. At higher moisture contents, the evaporation is approaching the potential one.

From the graphs of Figs. 6 and 7, it is obvious that the evaporation and IR-contrasts versus soil water content are highly influenced by the soil type as well. Sand soils keep a high evaporation rate down to water contents of a few per cent, while fine-grain clay and humus soils reduce the evaporation rate at much higher soil-moisture levels.

Consequently, an improved relationship between the IR-contrast and the water-content can be derived, if the soil-type influence is compensated for. At an earlier field measurement, it was found that the correlation between soil-moisture and IR-temperature at noon was improved from -0.62 to -0.91, when soil samples with sand contents above 40% were removed from the data analysis [3]. By night, the evaporation is reduced. As a consequence, the night surface temperatures are strongly related to the thermal inertia, which seems less sensitive to soil type than the evaporation effect. This conclusion is supported by the results of the correlation analysis in [3] .

5. COMPARISON WITH SIMULATION RESULTS

The measurements on thin soil layers made it possible to study the soil moisture influence on albedo, emissivity and evaporation, including the soil-type dependence.

This type of experiment, however, does not describe in a realistic way the effects of thermal inertia, which highly influences the surface temperature and heat flux of the top soil in a field environment. Consequently, the thermal inertia influence has to be studied by well-controlled field experiments in a larger scale. An alternative approach is to develop a computer model and predict by simulations how various parameters influence the IR-temperature.

Figure 9 displays some simulation results, which were derived by using a finite difference model based upon the equations shown in Fig. 1. A similar model was developed by Kahle [5] and Rosema [6] . The graphs show the influence of albedo (A), thermal inertia (P), and evaporation, where M is the ratio between the actual evaporation and the potential one of a wet surface at the same surface temperature.

Submodels developed by de Vries [7] or Pratt [8] were applied to estimate the soil moisture influence upon the thermal inertia. Predictions show that dry porous soils have a thermal inertia below $P = 1\ 000$, while soils near-saturated by water have P-values close to 2 000 (MKSA-units).

From the graphs, it is obvious that the evaporation effect generates a strong thermal-IR contrast betweeen dry and wet soil surfaces in the daytime. This contrast is enhanced by the increased thermal inertia at high water contents.

When the albedo is reduced due to increased soil moisture, the absorption of solar energy will also increase. Hence, the albedo effect is counter-acting the influence of thermal inertia and evaporation upon the surface temperature. Even if the last two effects usually dominate, the albedo influence and its dependence on soil moisture cannot be neglected at accurate modelling or data interpretation. The results of the simulation also indicate that the emissivity variations with soil water content have a less influence on the temperature contrast than the other parameters involved.

For dense fine-grained soils even a thin dry top layer highly reduces the evaporation. In that case, the increased thermal inertia from lower depths gives a dominating effect. Simulation results predict that the thermal inertia effect from deeper layers decreases significantly when the thickness of the dry top soil layer is about one centimetre.

Theoretical modelling will also explain the different dependence of reflectance and emissivity on soil moisture as indicated by Figs. 2 and 3. The thickness of the water film around the soil particles has to exceed one tenth of a wavelength in order to give reflectance and emissivity values, which significantly differ from the dry ones. Since the wavelength in the thermal-IR band (10 µm) is about 20 times the visible ones, higher soil-moisture contents are required to make the IR-emissivity change.

6. CONCLUSIONS

Both experimental and theoretical results show that the evaporation in the daytime has a great influence upon the thermal-IR signature. In particular, by night and dry top soils, which means a reduced evaporation, the thermal inertia and its relation to the soil moisture content of the top layer becomes much important. The results of the small-scale experiments on thin semi-dry soil layers also indicate that the changes of emissivity, albedo and IR-contrast with soil-moisture show different behaviour, which is influenced by the soil type as well.

In thermal modelling for predictions of the diurnal surface temperature variations, the soil moisture and soil type influence upon emissivity, albedo and evaporation should be included. From Figures 2, 3 and 7, we can easily define analytical relationships, which show how emissivity, albedo and the evaporation capability (M) depend on soil-moisture and soil-type. Further improvements are possible by applying a coupled multi-layer model, which describes the heat exchange and water transport in the top soil and the atmospheric boundary layer.

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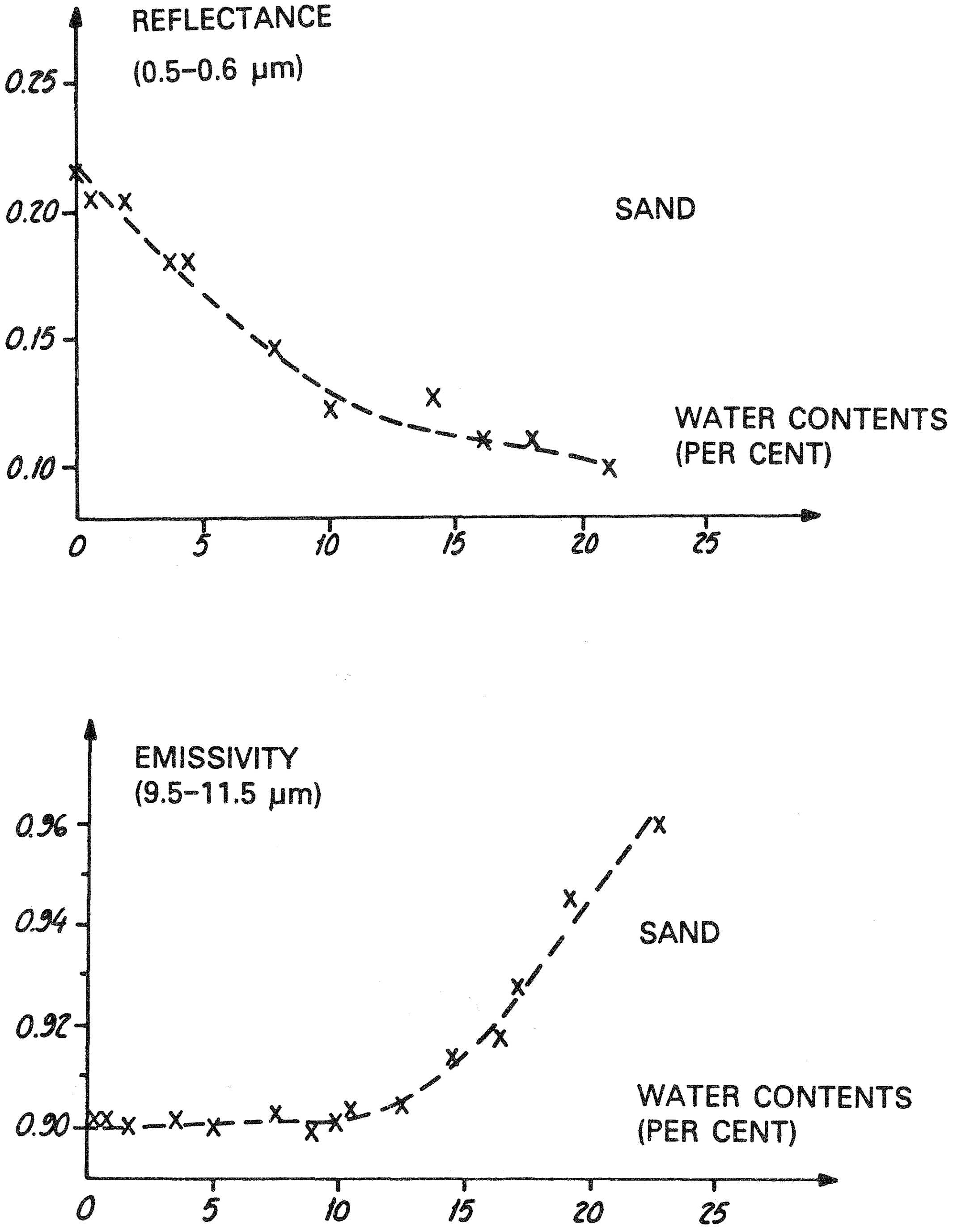

Figure 2. Measured emissivity and reflectance of sand versus weight fractions of soil moisture.

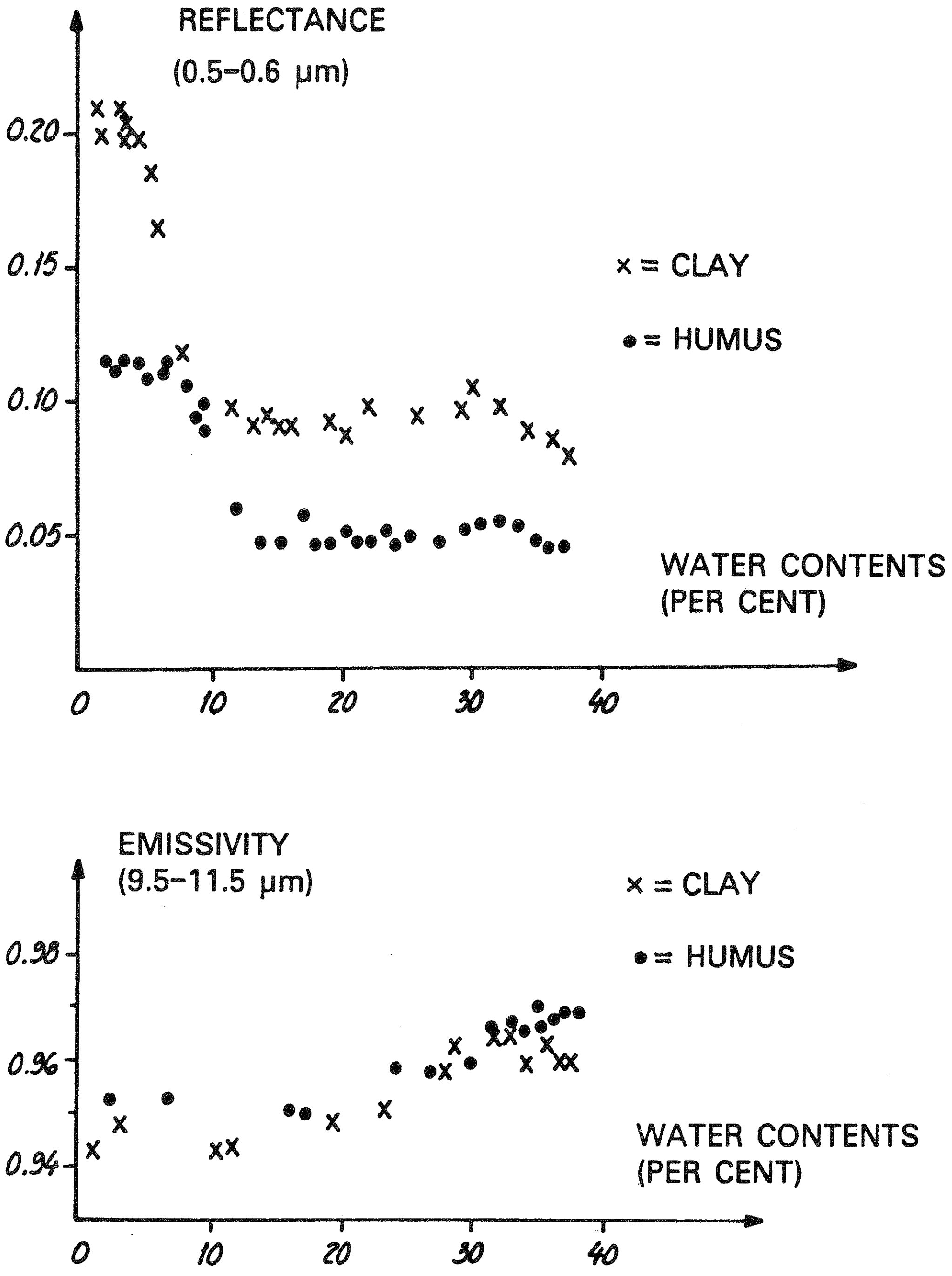

Figure 3. Measured emissivity and reflectance of clay and humus soils versus weight fractions of soil-moisture.

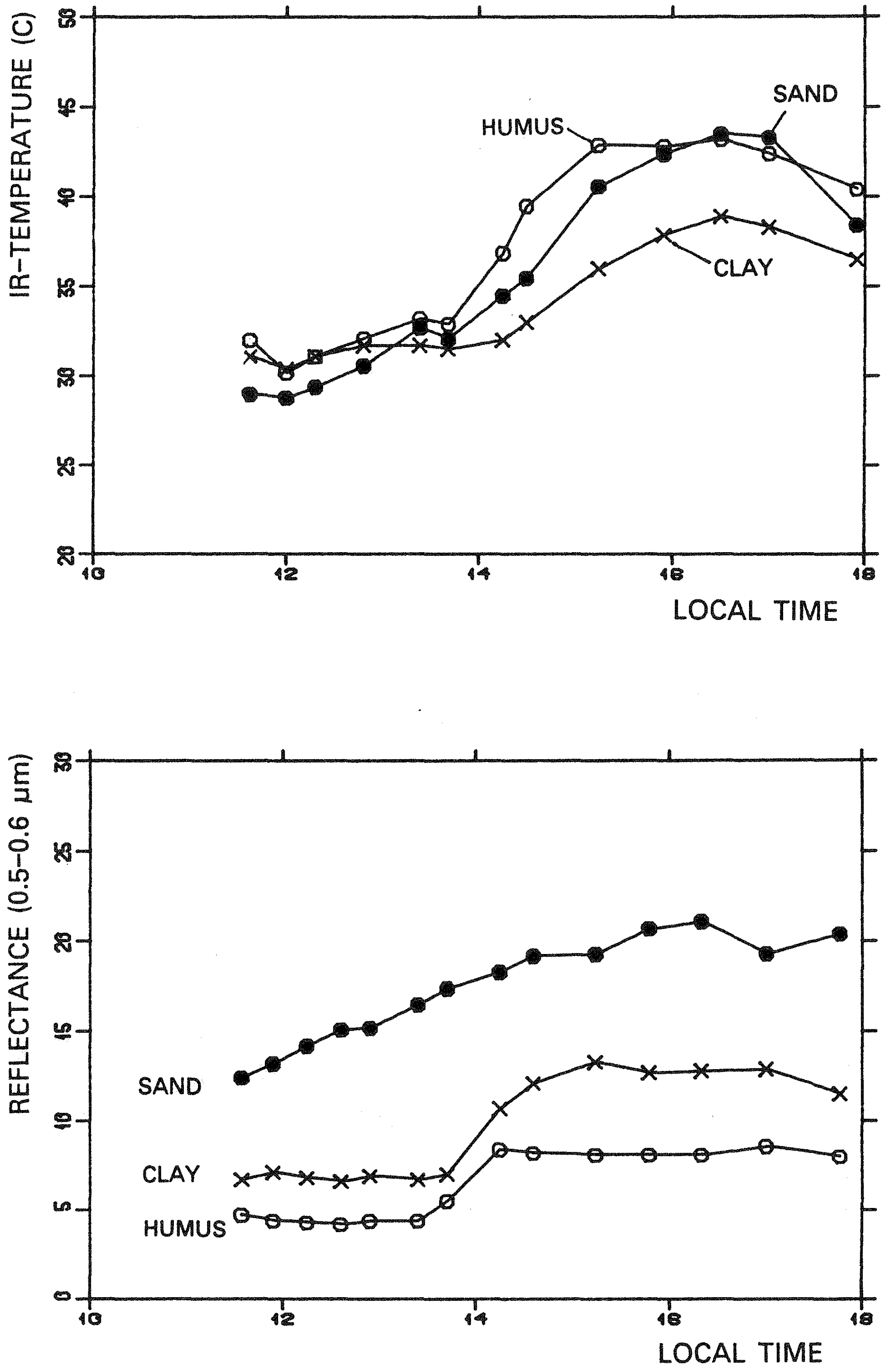

Figure 4. Time variation of the IR- temperature and reflectance during the drying phase for sand, clay and humus soils. From the June-experiment, 1986.

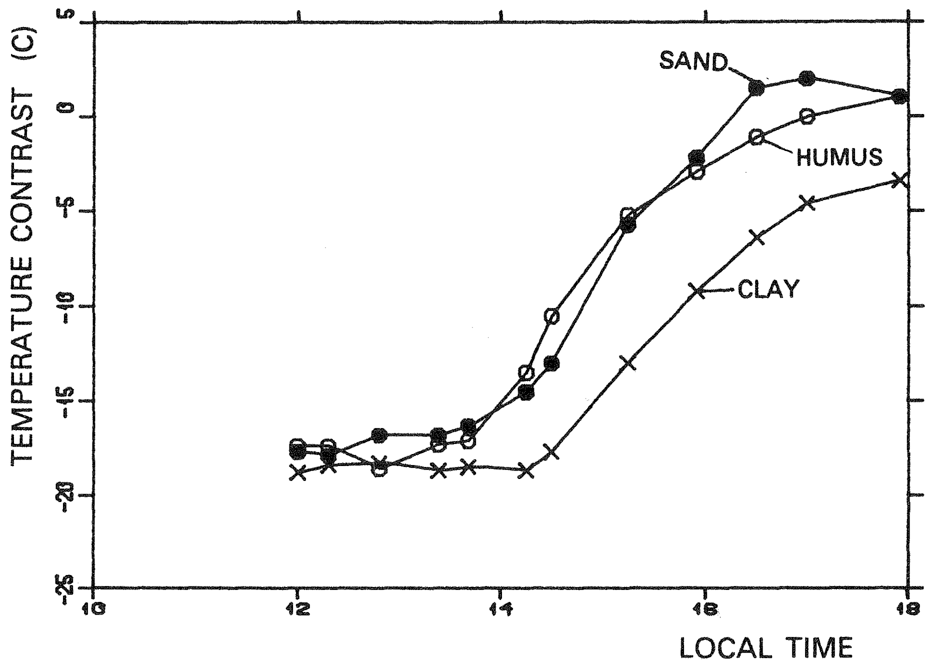

Figure 5. Temperature contrast between the drying soil sample and a dry reference soil. From the June-experiment, 1986.

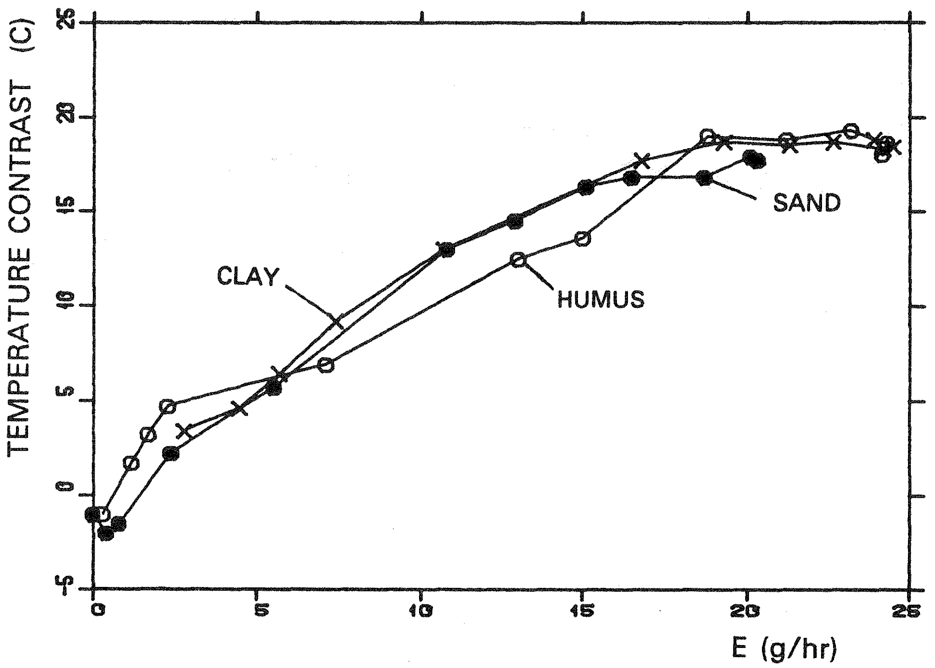

Figure 6. Measured IR-contrast versus the evaporative weight losses E (g/hr).

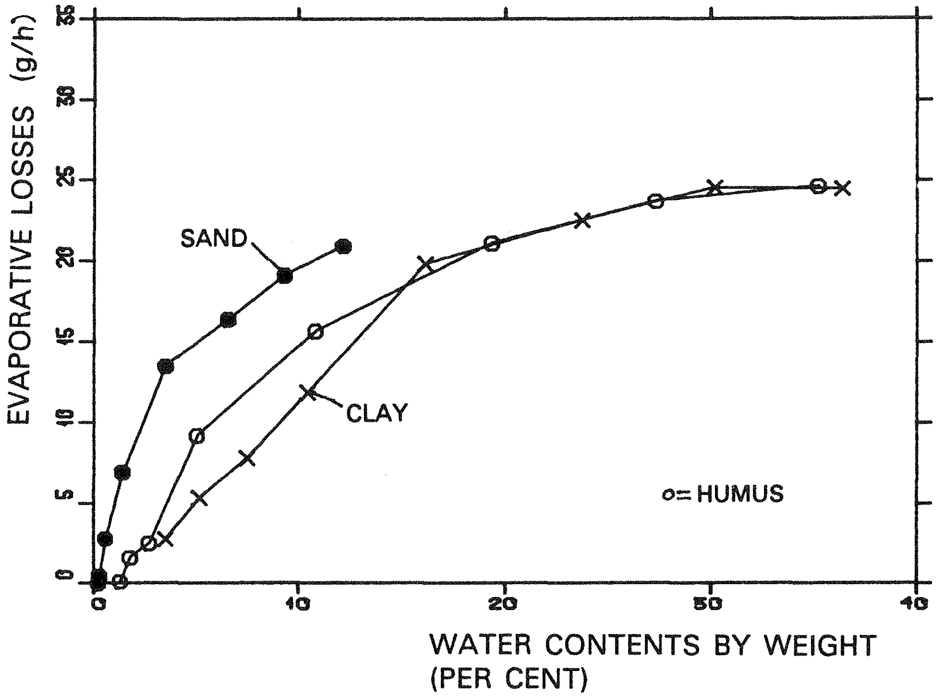

Figure 7. Evaporative losses (g/hr) versus gravimetric soil moisture for sand, clay and humus.

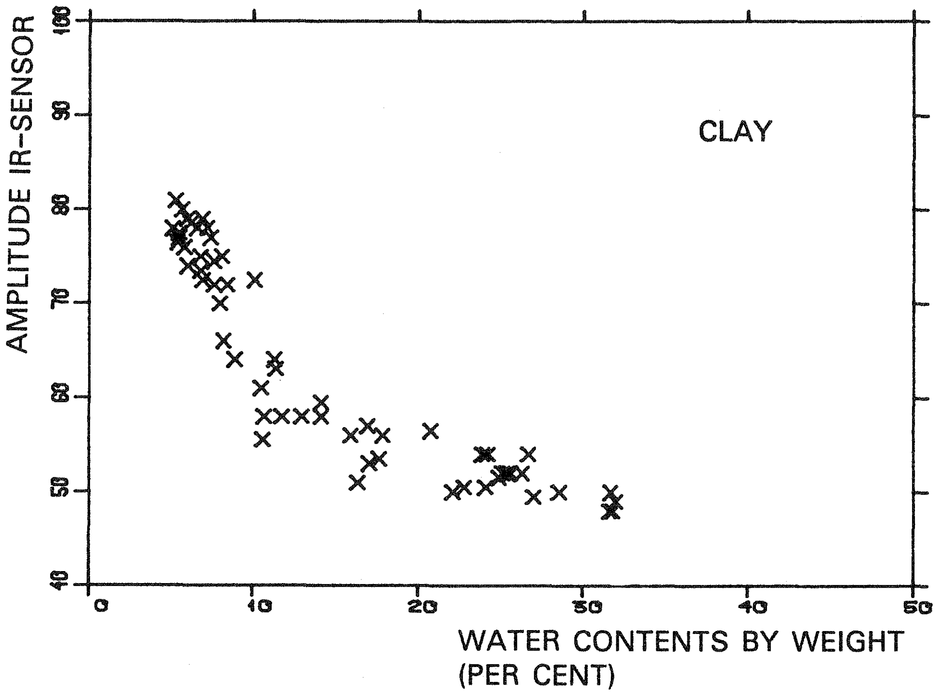

Figure 8. Relationships between the IR-amplitude and the gravimetric soil moisture (top centimeter) for a clay soil, which was irrigated two days before the measurement.

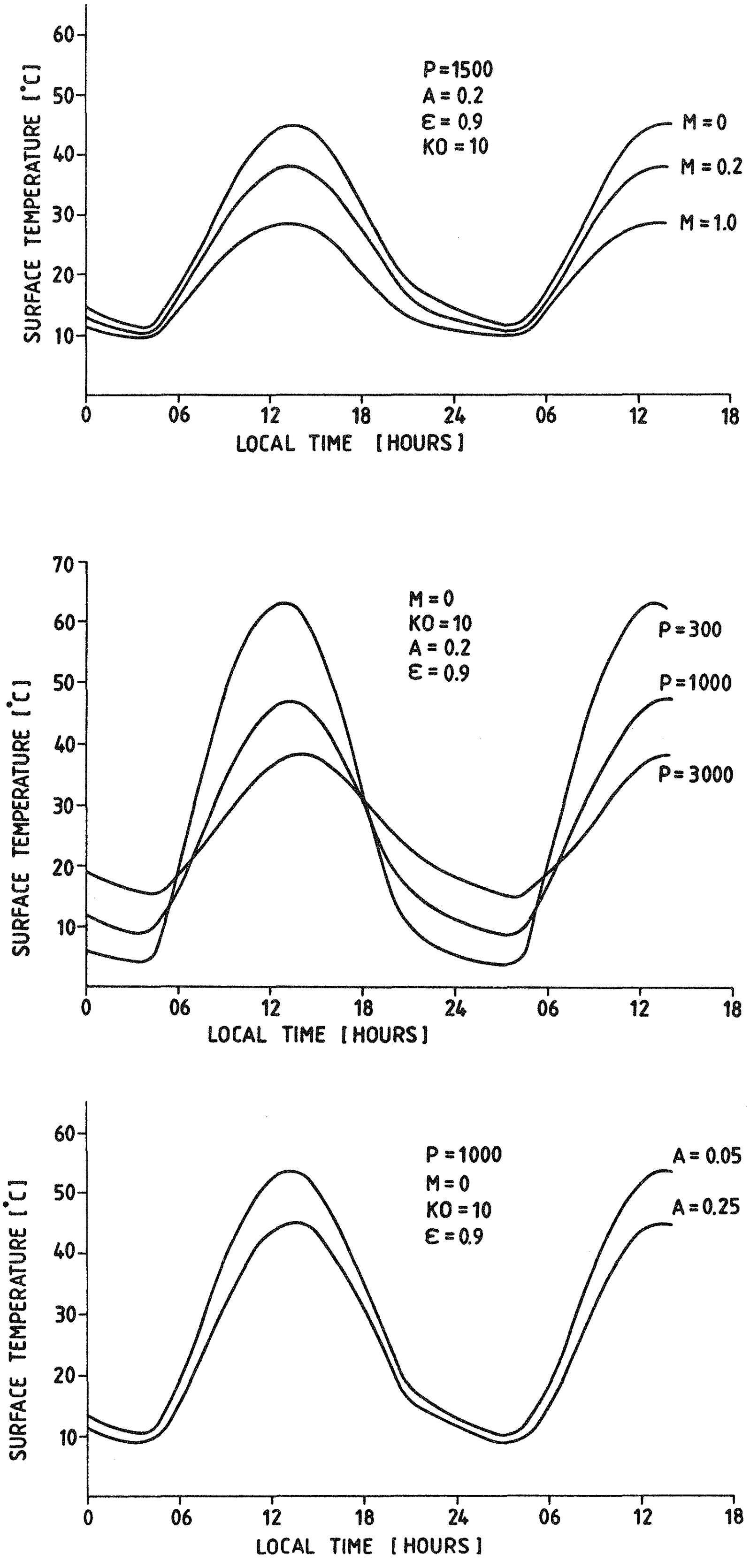

Figure 9. Predicted influence of evaporation, thermal inertia and albedo upon the diurnal surface temperature variations for a summer-day with calm weather and clear sky.